New Crops

Cuphea Seed Yield Response to Harvest Methods Applied on Different Dates

Marisol T. Berti,* Burton L. Johnson, Russ W. Gesch, and Frank Forcella

ABSTRACT

Cuphea, *Cuphea viscosissima* Jacq. × *C. lanceolata* W.T. Aiton, is a new crop that produces seed containing oil rich in medium-chain fatty acids. Because cuphea has an indeterminate growth habit, timing of harvest is difficult to determine. The objective of this study was to determine the optimum harvest time and technique for maximizing seed yield. This research was conducted at Prosper, ND, in 2005 and 2006; Carrington, ND, in 2005; and Morris, MN, in 2005 and 2006. The experimental factors were four harvest treatments, direct-nondesiccated (DND), direct-desiccated (DD), swathed (SW), and desiccated-swathed (DSW) applied on three different dates (D1, D2, and D3). Maximum seed moisture was 544 g kg^{-1}, but seed moisture decreased 181 g kg^{-1} as the harvest date was delayed for the DND-harvest treatment. Seed moisture reduction for the SW-harvest treatment compared with the DND-harvest treatment was 216 g kg^{-1} for D1. Swathing would be a better method than direct harvest or desiccation to reduce seed moisture at harvest. The harvested seed yields were not significantly different ($P \leq 0.05$) among the DND-, DD-, and SW-harvest treatments. Harvested seed yield reduction was observed only for the DSW-harvest treatment. Swathing is also acceptable since no significant seed yield reduction was observed. Based on the returns after harvest treatments, the DND-harvest treatment may be the most cost effective method to harvest cuphea seeds; however, it is not the most practical due to clogging of harvesting equipment, which slows down harvest.

Cuphea is being developed for the north-central United States as an industrial oilseed crop rich in medium-chain fatty acids (MCFA). These fatty acids are important in the manufacturing of soaps and detergents, and currently there is no domestic source of oil rich in MCFA. All MCFA used in the United States are derived from imported coconut oil (*Cocos nucifera* L.), palm kernel oil (*Elaeis guineensis* Jacq.) (FAO, 2006), or petrochemicals. Cuphea oil can also be used to manufacture personal care products (Brown et al., 2007). Recent studies indicate that cuphea crude oil is a potential substitute for diesel fuel (Geller et al., 1999). Estolides derived from cuphea fatty acids can be used to manufacture biodegradable engine lubricants (Cermak and Isbell, 2002, 2004).

Although efforts have been made to define best management practices to promote commercial cuphea production, little is known regarding optimum harvest techniques (Gesch et al., 2002b, 2005; Forcella et al., 2005b). Cuphea has an indeterminate growth and as seed capsules mature at the bottom of the stem, flowers are still developing at the top of the plant. The first maturing seed capsules shatter their seed before the capsules at the top of the plant have matured. Seed at harvest is a mixture of different maturity stages and, as a result, have a high moisture content. Cuphea seed moisture has been reported as high as 600 g kg^{-1} in early September harvest dates in west central Minnesota (Forcella et al., 2007). In North Dakota, many crops are treated with chemical harvest aids paraquat (1,1′-dimethyl-4,4′-bypridinium dichloride), sodium chlorate, and glyphosate (2-phosphonomethylglycine acid) before harvest to accelerate the decrease of seed moisture (Zollinger, 2007). One of the potential disadvantages of crop desiccation is seed shatter losses that can occur. For indeterminate crops, such as cuphea, seed will shatter naturally before the first frost even without the application of a desiccant (Gesch et al., 2002b, 2005, 2006). Seed losses of approximately 83 kg ha^{-1} due to shattering of direct-harvested cuphea have been reported by Gesch et al. (2005).

Swathing has been proposed as a method to reduce seed moisture at harvest. Forcella et al. (2007) demonstrated that seed moisture could be decreased from 670 to 250 g kg^{-1} after 2 wk of drying in windrows. Swathing and windrowing shattering losses for cuphea have been estimated at less than 100 kg ha^{-1} in west central Minnesota (Forcella et al., 2007).

Reducing seed moisture by swathing decreases seed drying costs, which can be a significant economic factor, especially as fuel costs continue to rise. Cuphea seeds are usually dried to 110 to 130 g kg^{-1} for storage (Cermak et al., 2005).

The objectives of this study were to evaluate harvest treatments applied on three dates on maximizing cuphea seed yield and oil content, while minimizing seed moisture.

Abbreviations: D1, date 1; D2, date 2; D3, date 3; D4, date 4, D5, date 5, direct-harvest dates 1 through 5; DND, direct-nondesiccated; DD, direct-desiccated; GDD, growing degree days; DSW, desiccated-swathed; MCFA, medium-chain fatty acid; RBHT, returns before harvest treatments; RAHT, returns after harvest treatments; SW, swathed.

M.T. Berti, Facultad de Agronomía, Universidad de Concepción, Chillán, Chile; B.L. Johnson, Dep. of Plant Sciences, North Dakota State Univ., Fargo, ND 58105-5051; R. Gesch and F. Forcella, USDA-ARS, North Central Soil Conservation Res. Lab., 803 Iowa Ave., Morris, MN 56267. Received 27 July 2007. *Corresponding author (mberti@udec.cl).

Published in Agron. J. 100:1138–1144 (2008).
doi:10.2134/agronj2007.0263

MATERIALS AND METHODS

Field Establishment and Experimental Design

This research was conducted at the Prosper, ND (47°0´ N, 97°3´ W, elev. 280 m) research site associated with the North Dakota Agricultural Experimental Station at Fargo, ND, and at the USDA-ARS Swan Lake Research Farm, Morris, MN (45°59´ N, 95°91´ W, elev. 344 m), in 2005 and 2006. The experiment was also conducted at Carrington, ND (47°30´ N, 99°8´ W, elev. 489 m), in 2005. Soil at Prosper is a Perella–Bearden silty clay loam (Perella: fine-silty, mixed, superactive Typic Endoaquoll; Bearden: fine-silty, mixed, superactive, frigid Aeric Calciaquoll). At Morris, the soil is a Heimdahl loam (coarse-loamy, mixed, superactive, frigid Calcic Hapludoll) (Soil Survey Staff, 2007) and at Carrington the soil is a Sverdrup sandy loam (fine-loamy, mixed, frigid Calcic Hapludoll).

At each site the experimental design was a randomized complete block with a factorial arrangement (3 × 4) with 12 treatments and four replicates at all environments (Steel and Torrie, 1980). The factors were four harvest treatments, direct-harvest-nondesiccated (DND), direct-harvest-desiccated (DD), swathed (SW), and desiccated-swathed (DSW) applied at each of three dates, (D1, D2, and D3). Paraquat was applied at 1.4 kg a.i. ha^{-1} on desiccation treatments. The harvest dates were spaced approximately 7 d apart with the first harvest date targeted at approximately 1000 to 1100 growing degree-days (GDD) from planting when possible (Table 1).

One additional harvest date treatment, harvested-direct only, was applied at Carrington in 2005 (DND at D4), and two additional harvest date treatments (direct-harvest only) (DND at D4 and D5) were applied at three other environments (Prosper 2005 and 2006, and Morris 2006). The five direct-harvest dates (DND from D1 to D5) were analyzed separately from the DD, SW, and DSW treatments. Direct-nondesiccated, DD, SW, and DSW plots were harvested at approximately 0, 7, 7, and 14 d after treatment, respectively. The DSW treatment occurred in two 7-d phases with swathing 7 d after desiccation, and harvest 7 d after swathing or 14 d after desiccation.

Each experimental plot was 5 m long with 6 rows spaced 0.31 m apart at Prosper and Carrington. At Morris, the row spacing was 0.61 m. Seeding dates and harvest dates for each environment are indicated in Table 1. Cuphea was sown at 21 kg ha^{-1} pure live seed at a seeding depth of 13 mm at all environments except at Morris, where the seeding rate was 8 kg ha^{-1} and the seeding depth was 15 mm. Soil fertility was adjusted to 90 kg ha^{-1} of N in the top 0.60 m of the soil profile, with the addition of dry urea fertilizer, at the Prosper and Carrington environments. At Morris, fertilizer was broadcast after sowing at rates of 70, 30, and 30 kg ha^{-1} N, P, and K, respectively.

Weeds were controlled with trifluralin [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine] applied preplant incorporated at 0.5 kg a.i. ha^{-1} followed by hand-weeding as needed at all environments. At Morris, mesotrione (2-[4-methylsulfonyl)-2nitrobenzoyl]-1,3 cyclohexanedione) at 0.1 kg a.i. ha^{-1} was applied post-emergence for broadleaf weed control. Forcella et al. (2005a) reported that cuphea has excellent tolerance to both herbicides. None of these herbicides are registered for use in cuphea.

Table 1. Seeding, treatment and direct-harvest dates, associated growing degree days (GDD) from planting, cumulative rainfall, and cumulative evapotranspiration (PET) between harvest dates at Prosper, ND, and Morris, MN, in 2005 and 2006, and Carrington, ND, in 2005.

Environment	Seeding date	Dates of treatment application (D) D1	D2	D3	D4	D5
Prosper 2005	19 May	7 Sept.	14 Sept.	20 Sept.	28 Sept.	7 Oct.
Prosper 2006	18 May	30 Aug.	6 Sept.	13 Sept.	20 Sept.	27 Sept.
Morris 2005	17 May	15 Sept.	24 Sept.	29 Sept.	–	–
Morris 2006	18 May	11 Sept.	20 Sept.	26 Sept.	2 Oct.	10 Oct.
Carrington 2005	31 May	12 Sept.	19 Sept.	26 Sept.	3 Oct.	–
		GDD from planting				
Prosper 2005†	19 May	1041	1105	1156	1197	1237
Prosper 2006†	18 May	1068	1128	1174	1216	1242
Morris 2005‡	17 May	1139	1168	1179	–	–
Morris 2006‡	18 May	1167	1219	1233	1242	1269
Carrington 2005†	31 May	957	998	1037	1083	–
		Cumulative rainfall between harvest dates, mm				
Prosper 2005		0.5	1.0	0.5	43.1	0
Prosper 2006		0	34.8	0	27.5	32.2
Morris 2005		0	11.1	11.9	–	–
Morris 2006		0	8.4	34.0	0	1.0
Carrington 2005		2.3	3.4	0	0	–
		Cumulative PET§ between harvest dates, mm				
Prosper 2005		3	34	31	35	36
Prosper 2006		7	34	36	25	17
Morris 2005		5	36	18	–	–
Morris 2006		34	19	20	28	–
Carrington 2005		3	29	32	45	–

† NDAWN, 2007.

‡ USDA-ARS, 2007.

§ PET was measured as potential evapotranspiration (Penman method).

All plots (5 m in length and the four center rows) were harvested with a self-propelled Hege 125B plot combine.[1] For the swathing treatments, the center four rows were cut by hand or with a tractor-mounted sicklebar at about 0.05 m above the soil surface and then windrowed by hand.

Growing degree days (GDD) from planting date were calculated for each of the harvest dates according to the formula

$$GDD = \Sigma[\ [(T_{max} + T_{min})/2)] - T_{base}]$$

where T_{max} and T_{min} are the maximum and minimum daily temperature, respectively, and T_{base} is the base temperature at which the crop grows. For this study, GDD were calculated with a base temperature of 10°C and an upper limit of 30°C following Gesch et al. (2002a).

Weather data were recorded at weather stations located less than 1 km from the experimental fields. These data was used to calculate cumulative potential evapotranspiration (PET) from the first to the fifth harvest date. Daily potential evapotranspiration was calculated for 2005 and 2006 for an alfalfa (*Medicago sativa* L.) reference with the Penmann equation (Montheith, 1965). Inputs for Penman method are solar radiation, air temperature, relative humidity, and wind speed.

To determine seed moisture, a 100-mL seed sample was taken from the harvested seed sample, right off the combine and before drying, for each plot and dried at 110°C for 48

[1] Mention of trade names, proprietary products, or vendors does not constitute a guarantee or warranty for the product by North Dakota State University and does not imply its approval to the exclusion of other products or vendors that may be suitable.

h. Seed moisture was determined by the gravimetric method weighing the seed before and after drying and calculating the moisture lost through drying.

Harvested seed yield was determined from the four center rows. The bulk-plot harvested seeds were dried to the same moisture of 120 g kg^{-1} cleaned to determine harvested seed yield. Then the seeds were stored in a cool room for 2 or 3 mo until oil determination.

Before determining oil content, seed samples taken from the bulk-plot harvested seeds were dried in an oven at 110°C for 3 h and then cooled to room temperature before the oil determination. Seed oil content was determined on 40 mL of clean dried seeds with a Newport 4000 Nuclear Magnetic Resonance (NMR) Analyzer, Oxford Institute Limited. Oil content was expressed on a dry weight basis. This is standard procedure for determining oil content of oilseeds (Robertson and Morrison, 1979).

Test weight was calculated by determining the weight of 40 mL of seed from a clean seed sample. Test weight was a better nonbiased measure than 1000-seed weight. Since cuphea plant is indeterminate, seed samples contained a mix of seeds of different sizes.

Seed shatter was measured by collecting seed in trays at four environments (Prosper in 2005 and 2006, Carrington in 2005, and Morris in 2005). Each seed tray was constructed from a section of PVC rain gutter 0.62 m in length and 0.18 m in width. Holes were drilled in the bottom of the rain gutter for rain water to drain. Then a nylon mesh screen was glued to the inside of the gutter to retain the shattered seeds above the bottom of the seed tray. This allowed water to drain from the tray. Seed trays were placed on the ground between the two center rows of each plot, about 2 wk before the first direct harvest date. This is before any seed shatter would occur. Insect or rodent damage or presence was not observed on the trays. Seeds were collected from the trays immediately before harvest and then placed back between the two-center rows to account for the amount of seed shattering during harvest. Seeds collected from the trays before and after harvesting were added together to estimate total seed shatter. Seed shatter was calculated as the seed weight (kg ha^{-1}) collected from the PVC trays expressed as a percentage of the total potential seed yield (kg ha^{-1}). Total potential seed yield was calculated as the harvested seed yield plus the estimated shattered seed yield.

An analysis of the different harvest treatments was made to determine the most economic treatment. Operating costs, revenues, returns before harvest treatments (RBHT), seed drying costs, cost of desiccation and swathing treatments, and returns after harvest treatments (RAHT) were calculated. For this study, the operating cost used was \$279 ha^{-1} for all harvest treatments, similar to that reported by Gesch et al. (2006). Operating cost per hectare included: tillage (\$30), planting (\$18), seed (\$8), herbicides (\$71), fertilizers (\$70), fuel (\$25), labor (\$15), and harvest (\$42) (Aakre, 2005). Direct combining cost was considered equal for all harvest treatments because estimating an extra cost associated with combine clogging when the material had too much moisture was difficult. Land, financial, and other fixed costs were not included in the analysis.

Revenues (gross income) per hectare were computed by multiplying harvested seed yield by its corresponding price (\$1.19 kg seed). Net returns before harvest treatments were computed by subtracting operating costs from gross revenues for each treatment as follows:

$$\text{RBHT} = (\text{Seed yield treatment} \times 1.19) - 279$$

According to the Grain Drying Cost Calculator (Edwards, 2007) using a propane value of \$5.6 L^{-1} (Energy Information Administration, 2007), the cost of drying seed is \$1.39 Mg^{-1} of seed for each 10 g kg^{-1} increment in water content. For seed drying cost calculations, target cuphea seed moisture was considered 110 g kg^{-1} (Cermak et al., 2005) The seed moisture to be lost was calculated as [seed moisture at harvest − 110 g kg^{-1}] and the cost of drying per hectare was calculated as [seed yield × 1.39/1000 × (seed moisture to be lost g kg^{-1})]. Three different RAHT were calculated using three different values of drying cost considering that propane value may increase or decrease in the future. Drying cost considered were \$1.00, 1.39, and 1.78 Mg^{-1} of seed for each 10 g kg^{-1} increment in water content reduced from the seed. According to this, values for RAHT with low, medium, and high cost of drying were calculated. Paraquat application (\$11.12 ha^{-1}) plus chemical (\$15 ha^{-1}) cost is approximately \$26.1 ha^{-1} (Zollinger, 2007). Swathing cost for canola (*Brassica napus* L.) is \$15 ha^{-1} in North Dakota and this value was used for cuphea swathing (Aakre, 2005). The net returns per hectare once harvest treatments and drying costs were included (RAHT) were calculated for each treatment as follows:

$$\text{RAHT direct harvest} = \text{RBHT} - \text{drying cost}$$

$$\text{RAHT desiccated} = \text{RBHT} - \text{drying cost} - \text{desiccation cost}$$

$$\text{RAHT swathed} = \text{RBHT} - \text{drying cost} - \text{swathing cost}$$

$$\text{Desiccated-swathed} = \text{RBHT} - \text{drying} - \text{desiccation costs} - \text{swathing costs}$$

Statistical Analysis

Statistical analysis was conducted by using standard procedures for a randomized complete-block design with a factorial arrangement (Steel and Torrie, 1980). Each location–year combination was defined as an "environment" and was considered a random effect in the statistical analysis. Harvest treatments and dates were considered fixed effects. Residual mean squares were compared for homogeneity among environments for each trait. If homogeneous, then a combined ANOVA was performed across environments. Means separation was performed by applying *F*-protected LSD comparisons at $P \leq 0.05$ level of significance. The estimated variance of pairwise mean differences and the corresponding degrees of freedom were calculated to estimate the correct LSD values for comparison of significant treatment means (Carmer et al., 1989). SAS System was used to process the data (SAS Institute, 2005). Direct harvest treatments from Dates 1 through 5 from the Prosper 2005 and 2006 environments were analyzed with a combined ANOVA.

RESULTS AND DISCUSSION

Climatic Information

Harvest maturity in cuphea is mainly related to accumulated GDD during the season but other factors can also influence maturity. Typically, water stress causes plants to accelerate their reproductive development. The 2005 growing season was unusually dry at Carrington in July and August when reproductive development occurs in cuphea (Table 2). The 2006 growing season was much drier than average at Morris and Prosper, which also affected reproductive development. Since harvest treatment and direct-harvest dates were targeted to start at approximately 1000 to 1100 GDD, the first harvest date in 2006 was about a week earlier than the previous year (Table 1).

The first killing frost, temperature ≤–2°C, occurred on 20 October and 9 October at Prosper, in 2005 and 2006, respectively, on 5 October at Carrington in 2005, and on 24 October and 11 October at Morris in 2005 and 2006, respectively.

Seed Moisture

Maximum seed moisture at harvest was 544 g kg^{-1} in D1 for the DND treatment, but decreased by 181 g kg^{-1} as the date was delayed to D3 (Table 3). For the DD-harvest treatment, seed moisture did not decrease significantly as harvest date was delayed. The objective of desiccation was to decrease seed moisture to ease harvesting (less clogging inside the combine) and reduce the cost of drying. Seed moisture reduction between the DND- and the DD-harvest treatments was 127 g kg^{-1} for D1, no significant differences between DND- and DD-harvest treatments were observed for D2 and D3 (Table 3).

A greater reduction in seed moisture than the one obtained was expected with the desiccation treatment. The interval between paraquat application and harvest was only 7 d, which may not have allowed a total dry down of the plant and seed. Therefore, it would be interesting to study and evaluate seed moisture reduction when harvesting at 14 d after desiccation. Seed moisture reduction for the SW- and DSW-harvest treatments compared with the DND-harvest treatment was 216 and 224 g kg^{-1}, respectively, for D1. No significant differences in seed moisture were observed for D2 and D3 among the harvest treatments. This may be because as the date was delayed, a longer time was required for drying. This could be due to lower air temperature, lower PET or higher rainfall between harvest dates. The potential evapotranspiration was similar between D1 and D2 at all North Dakota environments but decreased at Prosper 2006 after D3 (Table 1). At Morris environments PET decreased after the first week and remained at approximately 20 mm wk^{-1} after that, probably slowing down the seed-moisture loss. Differences in rainfall between D2 and D3 were only observed at Morris 2006 (Table 1).

Forcella et al. (2007) observed a 460 g kg^{-1} decrease in seed moisture when cuphea was swathed and windrowed and left 2 wk in the field, allowing for at least 30 mm of cumulative evaporation following swathing. In our study, cumulative evaporation fluctuated between 29 and 34 mm in only 7 d following swathing (Table 1), but we did not observe a seed-moisture reduction as the one observed by Forcella et al. (2007). Swathing may be a better method than desiccation, for reduction of seed moisture in cuphea as long as sufficient time is allowed for evaporative moisture loss.

Delaying direct-harvest from D2 to D5 reduced seed moisture at Morris in 2006 (Table 4). Cumulative PET at Morris 2006 was 100 mm from D1 to D5 (Table 1). At Prosper 2005, seed moisture decreased until D3, and then increased, which may be explained by rainfall the day before D4 (43.1 mm). Seed moisture reduction was 415 g kg^{-1}, delaying harvest 14 d, which would save \$57 Mg^{-1} (\$1.39 × 41.5) in seed drying costs. Seed moisture reduction at the end of the experiment at Prosper 2005 was 395 g kg^{-1} by delaying direct-harvest 28 d. This would save \$55 Mg^{-1} (\$1.39 × 39.5) in seed drying costs. Seed moisture did not decrease as direct-harvest was delayed at Prosper in 2006. This probably occurred because cuphea, an indeterminate plant, continued growing, flowering, and forming new seeds (high in seed moisture) due to optimum temperature and soil moisture during September; thus, seed moisture stayed the same throughout the harvest period.

Table 2. Growing-season rainfall for Prosper in 2005 and 2006, Carrington in 2005, and Morris in 2005 and 2006.

	Prosper			Carrington		Morris		
Month	2005	2006	30-yr avg.†	2005	30- yr avg.†	2005	2006	100-yr avg.‡
	mm							
May	64	41	68	69	57	76	47	71
June	161	12	91	161	93	155	28	95
July	34	66	82	15	104	82	27	86
Aug.	113	25	68	29	65	74	35	83
Sept.	104	95	54	6	62	118	116	61

† NDAWN, 2007.

‡ ARS-USDA, 2007.

Table 3. Mean seed moisture at harvest for the interaction between four harvest treatments and three dates averaged across five environments, Carrington 2005, Prosper 2005 and 2006, and Morris 2005 and 2006.

	Seed moisture		
Harvest treatment	D1	D2	D3
	g kg^{-1}		
Direct-nondesiccated (DND)	544	410	363
Direct-desiccated (DD)	417	375	375
Swathed (SW)	328	322	292
Desiccated-swathed (DSW)	320	293	331
LSD (P = 0.05)† 71			
LSD (P = 0.05)‡ 123			
LSD (P = 0.05)§ 111			

† To compare dates means within a harvest treatment.

‡ To compare harvest treatment means within a date.

§ To compare different date means with a different harvest treatment.

Table 4. Mean seed moisture of cuphea for five direct-harvest dates and three environments, Prosper 2005 and 2006, and Morris 2006.

	Seed moisture				
Environment	D1‡	D2	D3	D4	D5
	g kg^{-1}				
Morris 2006	–	584	524	492	387
Prosper 2005	597	315	182	241	202
Prosper 2006	429	431	412	425	435
LSD (P = 0.05)† 38					

† LSD for Environment × D interaction.

‡ Seed moisture for D1 at Morris, in 2006 was not recorded.

Table 5. Mean harvested seed yield, seed oil content, percentage seed shatter, seed shatter yield, and total seed yield of cuphea for four harvest treatments across three dates and four environments (Carrington 2005; Prosper 2005, 2006; Morris 2005).

Treatment	Harvested seed yield†	Seed oil content‡	Percentage seed shatter	Seed shatter yield	Total seed yield
	kg ha^{-1}	g kg^{-1}	%	—kg ha^{-1}—	
Direct-nondesiccated (DND)	375	281	17.0	64	439
Direct-desiccated (DD)	337	266	21.3	72	409
Swathed (SW)	320	258	26.0	83	403
Desiccated-swathed (DSW)	223	257	29.7	66	289
LSD (P = 0.05)	69	10	8.0	17	88

† Seed yield was calculated at 120 g kg^{-1} seed moisture.

‡ Seeds were dried for 3 h at 110°C before oil content determination. Oil content is expressed on a dry weight basis.

Table 6. Mean seed yield and seed oil content of cuphea for five direct-harvest dates and three environments, Prosper 2005, 2006; Morris 2005.

Environment	D1	D2	D3	D4	D5
			Seed yield†, kg ha^{-1}		
Morris 2006	441	505	380	255	215
Prosper 2005	251	371	415	553	300
Prosper 2006	347	417	441	346	362
Mean	346	431	412	385	293
LSD§ (P = 0.05) 95					
			Seed oil content‡, g kg^{-1}		
Morris 2006	263	245	240	232	213
Prosper 2005	269	280	282	290	282
Prosper 2006	319	314	332	312	297
Mean	284	279	285	278	264
LSD§ (P = 0.05) 24					

† Seed yield was calculated at 120 g kg^{-1} seed moisture.

‡ Seeds were dried for 3 h at110°C before oil content determination. Oil content is expressed on a dry weight basis.

§ LSD for Environment × D.

Harvested Seed Yield

Significant interactions among environment and both fixed effects were indicated from the ANOVA. Harvested seed yields were not significantly different among the three dates. The interaction between harvest date and harvest treatment was significant ($P \leq 0.05$). Harvested seed yield for the DND- and SW-harvest treatments did not vary as harvest was delayed while for the DD- and DSW-harvest treatments seed yield increased as harvest was delayed.

The harvest treatment main effect was significant. Harvested seed yields were not significantly different ($P > 0.05$) among the DND-, DD-, and SW-harvest treatments (Table 5). A reduction in harvested seed yield was observed only for the DSW-harvest treatment. Harvested seed yield reduction for this treatment was a result of seed shatter, since the plants were desiccated and 7 d later were swathed and 7 d later were harvested. This resulted in a 14-d period for seed shatter to occur. Although clogging during combining was not measured in this study, it was observed that the DND harvest treatment tends to clog much more than the other three treatments, which could be a serious limitation of this harvest method, although the effect of clogging on speed of harvest was not measured. According to this, swathing could be more practical and a faster method of cuphea harvest. Forcella et al. (2007) did not find seed yield differences between swath and direct-harvest treatments even after swath harvest was delayed 14 d. Seeding rates and row spacing although very different between the North Dakota and Minnesota sites was not expected to cause significant differences since it has been proven than cuphea plants plasticity allows them to compensate yield at a broad range of plant densities and row spacing (Gesch et al., 2003). Forcella et al. (2007) stated that swath density and width may have an influence on the amount of seed that ultimately falls through the swath onto the ground. Between-row-spacing could make a difference on seed shattering. With wider between-row spacing, plants are more lose on the canopy and can move about with the wind and shatter easily, whereas with a closer between-row spacing plants form a tight entangled canopy that reduces shattering. This was not measured on our experiment.

Harvested seed yield decreased at Morris in 2006 after the second direct-harvest date with 1219 accumulated GDD from planting (Tables 1 and 6), but at Prosper in 2005 seed yield increased until the fourth direct-harvest date (1197 GDD) and then declined. Harvested seed yield was not different among direct-harvest dates at Prosper in 2006. The results indicate that direct-harvest date had an influence on harvested seed yield at Morris in 2006 and at Prosper in 2005. Based on data from these two environments, the estimated optimum harvest date would be between the third and fourth week of September and approximately 1200 GDD from planting. At environments with adequate moisture in September, such as the Prosper 2005 environment, harvest should be delayed until capsules at the bottom of the plant begin to shatter (first shatter). If soil moisture is lacking in September, early harvest is recommended to reduce shattering losses. These results are similar to those reported by Gesch et al. (2005) at Morris, MN, where optimum harvest date corresponded with the last week of September, approximately 1200 GDD. The first killing frost did not occur until 20 October at Prosper in 2005 and 11 October at Morris in 2006.

Seed Oil Content

Seed oil content for cuphea was greater for the direct-harvest treatment compared with all the other harvest treatments (Table 5). This was probably due to a differential shattering of more mature seeds. Due to the indeterminate nature of cuphea, the first seeds to shatter are the most mature and highest in oil content (Berti et al., 2007). The remaining unopened seed capsules contain immature seeds lower in oil content.

Seed oil content for samples from the last harvest date from Morris in 2006 had significantly lower oil content than the first three harvest dates at the same environment (Table 6). No significant differences in oil content among harvest dates were observed at Prosper in 2005 and 2006. Gesch et al. (2005) reported a significant increase in seed oil content when cuphea was harvested at progressively later dates during August to September with a plateau occurring in late September. This effect was not observed in our studies. Gesch et al. (2005) obtained an increase in oil content because as harvest date was delayed he harvested the most mature seeds, which have higher oil content (Berti and Johnson, 2008). In our study, we did not select the seeds harvested. All seeds were considered on the sample for oil content analysis.

Test Weight

Test weight was greater at the Prosper 2006 environment, where the direct-harvest method produced the highest test weight compared with all other treatments (data not shown). The DND-harvest treatment also produced higher test weights at Carrington 2005 and Morris 2005, when compared with the DD-harvest treatment. This may be explained by shattering of the heavier seeds first. It was observed that desiccation with paraquat appeared to cause the capsules to burst open and quickly shed their seeds (data not shown).

Percentage Seed Shatter and Seed Shatter Yield

The DND-harvest treatment resulted in lower percentage seed shatter than the SW- and DSW-harvest treatments (Table 5). The SW treatment had the highest shatter yield but it was not different than the DD treatment. The percentage seed shatter and seed shatter yield were the greatest for the third and fourth direct-harvest date (D3 and D4), 21.6% and 90 kg ha^{-1} and 20.1% and 95.0 kg ha^{-1}, respectively (data not shown). The results of this study are similar to those found by Gesch et al. (2005), who estimated that seed yield losses due to seed shatter were from 50 to 100 kg ha^{-1}.

Total Seed Yield

Total seed yield was reduced by the DSW-harvest treatment (Table 5). Total seed yield was greatest on the fourth direct-harvest date at Prosper in 2005 (Table 7). This indicates that total seed yield of cuphea in eastern North Dakota potentially could be 690 kg ha^{-1} if shatter does not occur.

Economic Analysis

There were no interactions between harvest dates and treatments for the economic returns before and after harvest treatments; therefore, treatment means across three harvest dates and five environments are presented on Table 8. The lowest RBHT was for the DSW-harvest treatment since the lowest seed yield was observed for this treatment (Table 8). Although there were no significant differences among the other treatments, the DND-harvest treatment produced the highest economic return before and after harvest. For economic analysis the dollar value is more important than the statistical significance. Clearly the highest RAHT were obtained with the DND treatment; however, a lower RAHT would have been obtained if the cost due to clogging of harvest equipment would have been considered. Practically speaking, the DND treatment may not work in a large area of cuphea crop due to clogging of harvest equipment and slowing down of the harvest operation. Considering this, and from the point of view of a practical harvest operation, swathing or desiccation treatments could be used. The DND- and DD-harvest treatments had the highest cost of drying, but the SW-harvest treatment did not differ from the DD-harvest treatment. At a higher value of drying cost, RAHT decreases for the DND treatment but still is higher than swathing or desiccating.

Table 7. Mean total seed yield (harvested seed yield + seed shatter yield) of cuphea for five harvest dates and two environments.

Environment	Total seed yield				
	D1	D2	D3	D4	D5
	kg ha^{-1}				
Prosper 2005	310	439	527	691	373
Prosper 2006	389	449	509	397	399
Mean	350	444	518	544	387
LSD (0.05)† 106					

† To compare environment × direct-harvest date interaction.

Table 8. Returns before harvest treatments (RBHT), drying cost, and returns after harvest treatments (RAHT) for three values of drying cost (low, medium, high) for four harvest treatments across three dates and five environments (Carrington 2005; Prosper 2005, 2006; Morris 2005, 2006).

Harvest treatment	RBHT	Drying cost	RAHT		
			Low†	Medium	High
	$ ha^{-1}				
Direct-nondesiccated (DND)	168	16.0	156	152	147
Direct-desiccated (DD)	122	13.2	86	82	78
Swathed (SW)	102	9.6	80	77	75
Desiccated-swathed (DSW)	–14	6.6	–60	–62	–63
LSD‡ (0.05)	82	4.1		81	

† Drying cost used to calculate low, medium, and high RAHT was 1.00, 1.39, and 1.78 $ Mg^{-1} of seed for each 10 g kg^{-1} increments of water content reduced.

‡ LSD to compare among harvest treatments.

CONCLUSIONS

Seed moisture at harvest is an important factor to consider since wet seed requires drying before marketing or storage. Seed moisture decreased as the harvest date for the direct-nondesiccated treatment was delayed averaged across environments. Initial seed moisture and the rate of dry down were dependent on environmental weather conditions. Seed moisture did not decrease as harvest date was delayed at Prosper in 2006.

Cuphea can be direct harvested without desiccation at approximately 1200 to 1300 GDD, although seed drying would be necessary and clogging remains a problem, which will delay the harvest. Swathing is also acceptable since no significant seed yield reduction was observed, and the reduction in oil content was small compared with the gain in seed moisture reduction. Also no clogging was observed and the harvest was faster. The higher seed yield of the direct-nondesiccated harvest treatment and the lower expenses of not having to desiccate or swath the crop compensated for the higher drying cost. Based on the returns after harvest treatments, the direct-nondesiccated harvest treatment may be the most cost effective method to harvest cuphea seeds; however, is not the most practical due to clogging, which slows down harvest.

ACKNOWLEDGMENTS

Funding for this work was provided by the National Science Foundation award EPS-0447679, the North Dakota State Board of Agricultural Research and Education, and the North Dakota Agricultural Experiment Station.

REFERENCES

Aakre, D. 2005. Custom farm work rates on North Dakota Farms, 2004, by North Dakota farming regions. Bull. EC-499. North Dakota State Univ. Ext. Serv., Fargo.

USDA-ARS. 2007. Weather data from Swan Lake Research Farm. Available at http://www.ars.usda.gov/Services/docs.htm?docid=9682 (accessed 19 Mar. 2007; verified 19 May 2008). ARS-USDA North Central Soil Conservation Research Lab., Morris, MN.

Berti, M.T., and B.L. Johnson. 2008. Changes during physiological maturity of cuphea. Field Crops Res. 106:163–170.

Berti, M.T., B.L. Johnson, and L.K. Manthey. 2007. Seed physiological maturity in cuphea. Ind. Crops Prod. 25:190–201.

Brown, J.H., R. Kleiman, J. Hill, S. Koritala, and K. Lotts. 2007. Cosmetic and topical compositions comprising cuphea oil and derivatives thereof. U.S. patent U.S. 2007/0031354A1.

Carmer, S.G., W.E. Nyquist, and W.M. Walker. 1989. Least significant differences for combined analyses of experiments with two- or three-factor treatment designs. Agron. J. 81:665–672.

Cermak, S.C., and T.A. Isbell. 2002. Physical properties of saturated estolides and their 2-ethylhexylesters. Ind. Crops Prod. 16:119–127.

Cermak, S.C., and T.A. Isbell. 2004. Synthesis and physical properties of saturated cuphea-oleic estolides and esters. J. Am. Oil Chem. Soc. 81:297–303.

Cermak, S.C., T.A. Isbell, J.E. Isbell, G.G. Ackerman, B.A. Lowery, and A.B. Deppe. 2005. Batch drying of cuphea seeds. Ind. Crops Prod. 21:353–359.

Edwards, W. 2007. Grain drying cost calculator. Version 1.0. Available at www.extension.iastate.edu/agdm/decisionaidscd.html (accessed 25 Feb. 2007; verified 19 May 2008). Univ. Ext., Iowa State Univ., Ames.

Energy Information Administration. 2007 Propane prices. What consumers should know. Available at http://www.eia.doe.gov/pub/oil_gas/petroleum/analysis_publications/propane_prices_brochure/propbro.html (accessed May 2008; verified 28 May 2008) EIA, Washington, DC.

FAO. 2006. Agricultural data: Crops and livestock primary and processed. Available at http://faostat.fao.org (accessed 25 Feb. 2007; verified 28 May 2008) FAO, Rome.

Forcella, F., G.B. Admundson, R.W. Gesch, S.K. Paiernik, V.M. Davis, and W.B. Phippen. 2005a. Herbicides tolerated by cuphea (*Cuphea viscosissima* × *lanceolata*). Weed Technol. 19:861–865.

Forcella, F., R.W. Gesch, and T.A. Isbell. 2005b. Seed yield, oil, and fatty acids of cuphea in the Northwestern corn belt. Crop Sci. 45:2195–2202.

Forcella, F., K. Spokas, R.W. Gesch, T. Isbell, and D. Archer. 2007. Swathing and windrowing as harvests aids for cuphea. Agron. J. 99:415–418.

Geller, D.P., J.W. Goodrum, and S.J. Knapp. 1999. Fuel properties of oil from genetically altered *Cuphea viscosissima*. Ind. Crops Prod. 9:85–91.

Gesch, R.W., S.C. Cermak, T.A. Isbell, and F. Forcella. 2005. Seed yield and oil content of cuphea as affected by harvest date. Agron. J. 97:817–822.

Gesch, R.W., F. Forcella, N.W. Barbour, B. Phillips, and W.V. Voorheees. 2002a. Yield and growth response of *Cuphea* to sowing date. Crop Sci. 42:1959–1965.

Gesch, R.W., F. Forcella, N.W. Barbour, W.V. Voorheees, and B. Phillips. 2003. Growth and yield response of *Cuphea* to row spacing. Field Crops Res. 81:193–199.

Gesch, R.W., F. Forcella, A. Olness, D. Archer, and A. Hebard. 2006. Agricultural management of cuphea and potential for commercial production in the Northern Corn Belt. Ind. Crops Prod. 24:300–306.

Gesch, R.W., F. Forcella, and B.S. Sharratt. 2002b. Harvest date and method for *Cuphea* in the Northern corn belt. p. 10. *In* Annual Meeting of the Assoc. for the Advancement of Industrial Crops (AAIC), Saskatoon, SK, Canada. 25–28 Aug. AAIC, Maricopa, AZ.

Montheith, J.L. 1965. Evaporation and the environment. p. 205–234. *In* G.E. Fogg (ed.) The movement of water in living organisms. Proc. Soc. Exp. Biol. 19th Symp. Cambridge Univ. Press, Cambridge, UK.

NDAWN. 2007. North Dakota Agricultural Weather Network. Available at http://ndawn.ndsu.nodak.edu/ (accessed 19 Mar. 2007; verified 19 May 2008). North Dakota State Univ., Fargo.

Robertson, J.A., and W.H. Morrison. 1979. Analysis of oil content of sunflower seed by wide-line NMR. J. Am. Oil Chem. Soc. 56:961–964.

SAS Institute. 2005. The SAS system for Windows. Release 9.1. SAS Inst., Cary, NC.

Soil Survey Staff. 2007. Official Soil Series Descriptions. Available at http://soils.usda.gov/technical/classification/osd/index.html (accessed 20 July 2007; verified 19 May 2008). USDA-NRCS, Washington, DC.

Steel, R.G.D., and J.H. Torrie. 1980. Principles and procedures of statistics: A biometrical approach. 2nd ed. McGraw-Hill, New York.

Zollinger, R. 2007. North Dakota weed control guide. Ext. Serv. Bull W-253. North Dakota State Univ., Fargo.